

THE GENERAL WATER CIRCULATION OF SPENCER GULF, SOUTH AUSTRALIA, IN THE PERIOD FEBRUARY TO MAY

by D. A. BULLOCK*

Summary

BULLOCK, D. A. (1975).—The general water circulation of Spencer Gulf, South Australia, in the period February to May. *Trans. R. Soc. S. Aust.* **99**(1), 43–53, 28 February, 1975.

Historical temperature and salinity data are presented together with the three-dimensional velocity structure of the general water circulation of Spencer Gulf, deduced from the data using a numerical model. In the southern area of the Gulf a cyclonic gyre is found which exchanges Gulf water with the ocean water outside the Gulf. On the western coast of the Gulf, a moderate boundary flow, which is called the "Port Lincoln Boundary Current", is evident at all depths. The water in the northern portion of the Gulf circulates both in the vertical and the horizontal and appears to form an almost closed system separate from the system in the southern region.

Introduction

An investigation of the general water circulation in Spencer Gulf, and the region outside it, is made below from observation of property distributions and using a numerical model. The term "general water circulation" is used so that tidal currents which basically involve a periodic north-south movement of the Gulf's waters are excluded. Tidal currents can be superimposed on the more sustained flows caused by thermohaline (and wind) forcing which are particularly important because of the part they play in the interchange of water in a substantially enclosed body of water. Thermohaline currents are brought about by horizontal pressure gradients due to density variations in the Gulf, which are caused by temperature and salinity differences, produced in part by outside water entering the Gulf, and in part by variation in the effect of evaporation over the Gulf.

All available data for the region, obtained on C.S.I.R.O. cruises, are shown in Fig. 1. The cruises took place between 1961 and 1966 during the months indicated in the caption. No direct current readings are available, although some results on surface drift do exist from a drift card experiment (Marshall & Radok 1972).

Presentation and Interpretation of Cruise Data

Using measurements made by F.R.V. Investigator (C.S.I.R.O. Aust., 1968c) on 7 May 1964, a vertical salinity section (Fig. 2a) was drawn for a line across the mouth of Spencer Gulf from Port Lincoln on the western side to Corny Point on Yorke Peninsula. The salinity is approximately homogeneously distributed over depth for any particular water column, although around the centre the situation is closer to that of a two-layer system since the salinity is almost constant with depth until about 20 m, at which point a steep salinity gradient occurs. Below this, the salinity is again constant with depth but greater than before. Also, the salinity increases with distance from west to east, indicating that water enters the Gulf on the western side and leaves via the eastern side after its salinity has increased due to evaporation and mixing. The density section (Fig. 2b) has a similar form to the salinity section, indicating that salinity is the dominant factor in determining thermohaline flow.

The most important feature of the hydrology of Spencer Gulf, evident from all data (Figs 10, 11), is that the water is approximately homogeneous from top to bottom, and hence

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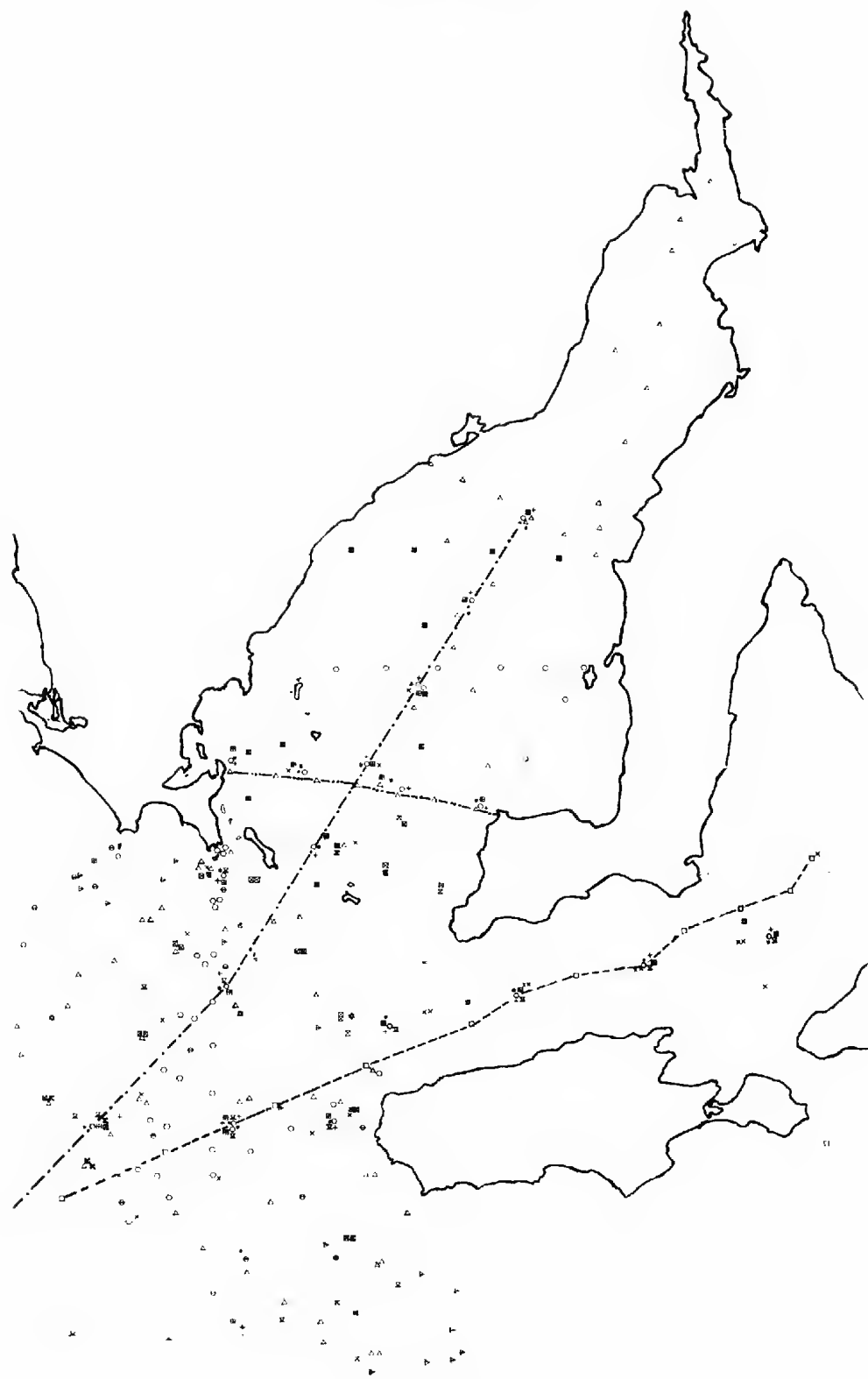


Fig. 1.

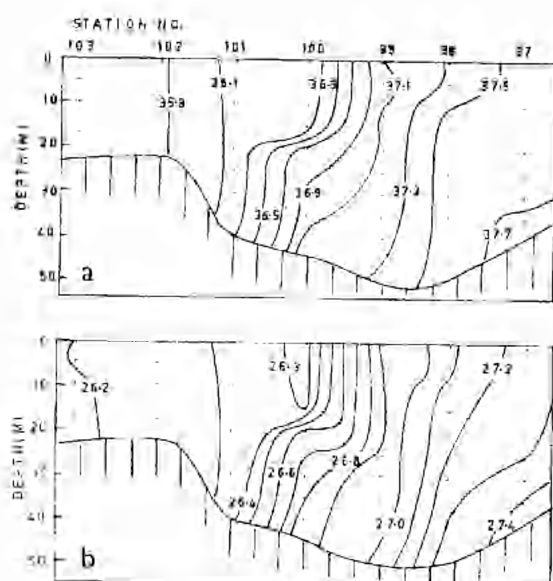


Fig. 2. Vertical sections across Spencer Gulf near the mouth, Marked — on Figure 1, data taken from CSIRO Aust. 1968, sampling depths indicated by dots.
(a) Salinity (‰), (b) σ_t .

it is reasonable that the quantities be represented by their depth-average. Fig. 3a-c shows horizontal depth-average distributions of salinity, temperature and density drawn from data obtained in the period 4-7 May 1964 (C.S.I.R.O. Aust. 1968c). Although other measurements have been made in Spencer Gulf, this cruise was by far the most comprehensive. From experience it was found necessary to restrict the data used to that obtained on one cruise, which spans only a short duration, so that seasonal and shorter term variations in properties do not cause misleading interpretations to be made.

The distributions shown in Fig. 3 are consistent with those in Fig. 2 and give additional information. A flow up the western shore is evident and it can be seen that the salinity increases eastward over the whole southern area of the Gulf indicating that the movement of water is basically clockwise. It appears that the advective exchange with the water outside the Gulf is limited to the area below a latitude of about $33^{\circ}45'S$. Above this region where the Gulf narrows, the water appears "blocked-in". Along the eastern and central areas of the upper part of the Gulf, the high salinity water seems to flow down the Gulf until it meets the lower salinity water taking part in the advective process described above.

The data from the northern part indicate that the water moves as a mass in phase with the tidal currents. At $34^{\circ}00'S$, $137^{\circ}10'E$, two stations (76 and 89) were occupied, separated by a period of 29 hours during which the depth-average salinity changed from 38.40‰ to 38.14‰ . At $33^{\circ}57'S$, $137^{\circ}25'E$ (stations 77 and 85), the salinities changed from 38.35‰ to 38.60‰ over a period of 21 hours. Using the horizontal salinity gradients at this location, Fig. 3 shows that this salinity variation corresponds to a tidal excursion of a few kilometres.

The mechanism responsible for the homogeneity of the water columns is based on vertical mixing promoted by tidal currents, which are amplified by the shallow water, running over a rough bottom which enhances vertical diffusion by the shear effect (Bowden 1965).

The temperature variation over the Gulf is small (Fig. 3b); a plausible explanation for this observation is the following. Since, in the north of the Gulf, the advective exchange of properties is small and the water shallow, the effects of evaporation are more marked than further south, as is reflected by the high salini-

Fig. 1. Location of Oceanographic Stations in the South Australian Gulf System until 1973.

Key to Symbols

- H.M.A.S. Gascoyne (G2/61) Feb.-March 1961 (CSIRO Aust. 1966)
- H.M.A.S. Gascoyne (G2/63) March 1963 (CSIRO Aust. 1967a)
- ◐ H.M.A.S. Gascoyne (G5/65) March-April 1965 (CSIRO 1967b)
- H.M.A.S. Gascoyne (G2/62) June-Aug. 1962 (CSIRO Aust. 1967c)
- ▨ H.M.A.S. Gascoyne (G2/64) Feb. 1964 (CSIRO Aust. 1967d)
- ▩ H.M.A.S. Gascoyne (G2/65) Feb. 1965 (CSIRO Aust. 1968a)
- + H.M.A.S. Diamantina (Dm2/66) April 1966 (CSIRO Aust. 1969)
- ✱ F.R.V. Investigator 1963 (CSIRO Aust. 1968b)
- ◁ F.R.V. Investigator 1964 (CSIRO Aust. 1968c)
- × F.R.V. Investigator Dec. 1962 (CSIRO Aust. 1968d)
- ◊ F.R.V. Investigator Feb. 1965 (CSIRO Aust. 1968e)
- F.V. Estelle Star April-May 1965 (CSIRO Aust. 1968f)
- F.V. Estelle Star April 1966 (CSIRO Aust. 1968g)
- F.R.V. Weerrutta Jan.-March 1961 (CSIRO Aust. 1968h)

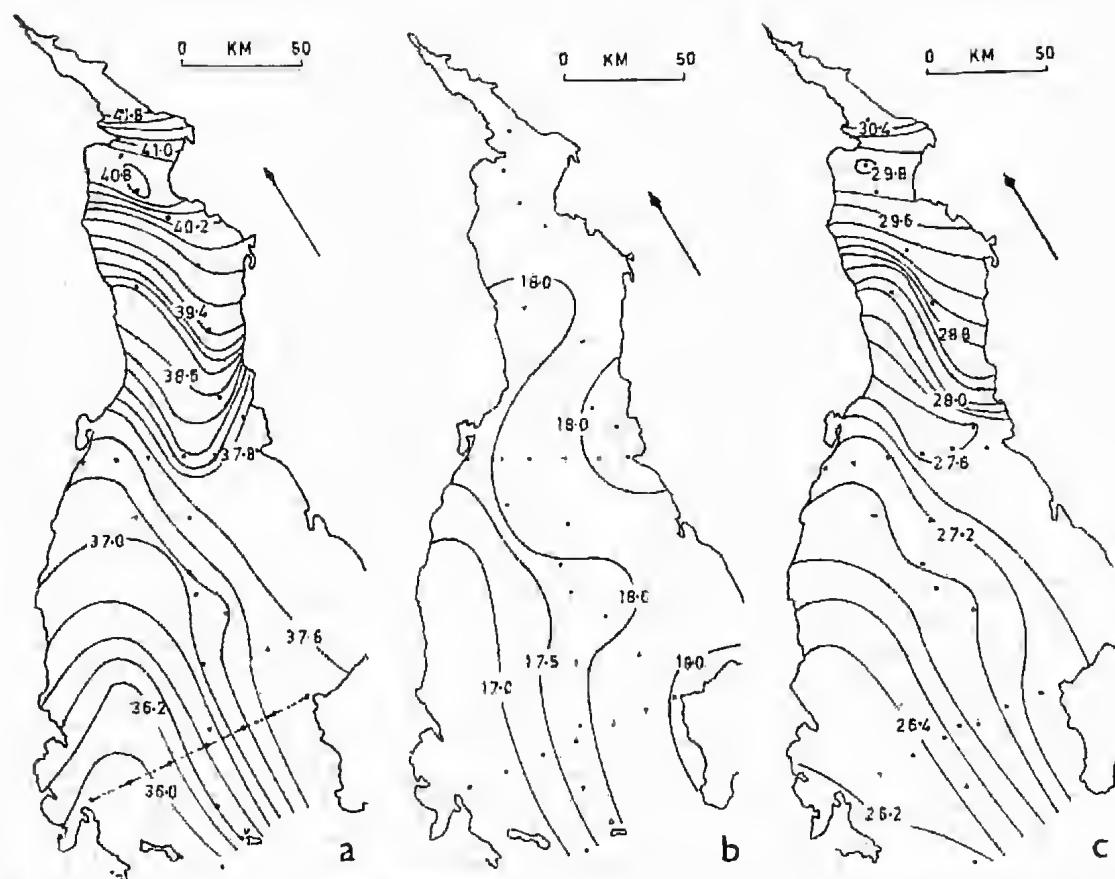


Fig. 3. Horizontal depth-average distributions in Spencer Gulf. Data taken from CSIRO Aust. 1968c. (a) Salinity (‰), (b) Temperature ($^{\circ}\text{C}$), (c) σ_t .

ties. The process of evaporation requires the extraction of latent heat of vaporisation which in turn lowers the temperature and nullifies the effect of direct heating. The following rough calculation shows that there is an approximate balance between the heat input from the atmosphere and the heat output due to evaporation. From Haney (1972), the heat flux/unit area is proportional to the difference between the apparent air temperature and the sea temperature (denoted by T_a^* and T_s respectively). Assuming this flux is all available for evaporation, we obtain

$$E = \lambda(T_a^* - T_s)$$

where E is the evaporative heat flux/unit area, and approximately $\lambda = 34 \text{ Wm}^{-2}(\text{^{\circ}C})^{-1}$ (Haney 1972). Taking the values, $T_a^* = 21^{\circ}\text{C}$ (the mean temperature for early April), and $E = 100 \text{ Wm}^{-2}$, and substituting in equation (1) yields $T_s = 18^{\circ}\text{C}$, which is approximately the

observed value (Fig. 3b). The neglect of advective exchange is justifiable in view of the observed small variation of temperature and closed nature of the circulation in the northern Gulf. Vertical mixing maintains the temperature difference between the atmosphere and the sea surface.

Locations of the stations are shown by the dots in Fig. 3a-c; stations were not occupied in some areas, notably above Hardwick Bay on the eastern side of the Gulf. Nevertheless, the overall pattern of water properties can be inferred reasonably accurately.

The Numerical Model

In order to investigate whether the above circulation could be considered as primarily due to thermohaline forcing or whether some other cause such as wind is dominant, and discover in greater detail the dynamics of Spencer Gulf, a numerical model was used to derive theoretic-

tically the field of flow from the density field shown in Fig. 3c. The model entitled FLOWDEN computes the currents generated in a sea of density independent of depth, by wind and variations in atmospheric pressure, and by the

horizontal pressure gradients induced by the density field¹. This is done by solving the finite difference representation of the component transport equations written in a form applicable to the terrestrial situation².

$$\frac{\partial U}{\partial t} = fV - gH \frac{\partial \eta}{\partial x} - g^* \frac{H^2}{2} \frac{\partial \sigma_t}{\partial x} + \frac{\tau_{sx}}{\rho_0} - K|u_B|u_B \quad (2)$$

$$\frac{\partial V}{\partial t} = -fU - gH \frac{\partial \eta}{\partial y} - g^* \frac{H^2}{2} \frac{\partial \sigma_t}{\partial y} + \frac{\tau_{sy}}{\rho_0} - K|v_B|v_B \quad (3)$$

where the following notation is used:

$$U = \int_{-H}^{\eta} u dz, \quad V = \int_{-H}^{\eta} v dz$$

u = eastward component of velocity (east = x direction)

v = northward component of velocity (north = y direction)

u_B, v_B = x & y components of bottom velocity (u_B)

z = distance measured perpendicular to earth's surface, positive upwards

σ_t = $(\rho - 1) \times 10^4$, ρ in kg l^{-1}

f = Coriolis parameter = $2\omega \cos \phi$, ω = angular speed of the earth's rotation, ϕ = latitude

H = depth

g^* = $10^{-3} \alpha_{35.0,0} g$, $\alpha_{35.0,0}$ = specific volume of the standard ocean

g = gravitational acceleration

η = sea surface elevation

K = bottom drag coefficient

ρ_0 = density of a standard ocean = $\frac{1}{\alpha_{35.0,0}}$

τ_{sx}, τ_{sy} = x & y components of surface wind stress

The terms in equations (2) and (3) have the following physical meanings: the left-hand sides are the linearized accelerations, the first terms on the right-hand sides are the Coriolis accelerations, the second terms are the horizontal pressure gradients due to elevation of the surface, the third terms are the thermohaline terms which take into account the horizontal pressure gradients due to the inhomogeneity of the horizontal salinity and temperature distributions. The final two terms are stress terms describing wind and bottom friction respectively.

The magnitudes of the thermohaline terms were evaluated using another computer programme from the observed density distribution (Fig. 3c) and the depths were interpolated from those given on a naval hydrographic chart. A typical value of the x component of

the thermohaline terms was $300 \text{ mm}^2 \text{ s}^{-2}$. This can be compared with the typical magnitude of $100 \text{ mm}^2 \text{ s}^{-2}$ for the forcing term corresponding to wind stress, so that the circulation in Spencer Gulf due to thermohaline causes can be expected to be quite significant. The bottom drag coefficient $K = .0025$.

FLOWDEN was run with the precalculated thermohaline term as the only forcing term and with the thermohaline term together with a constant wind. After the equivalent of 17 hours an equilibrium current was reached (actually a small oscillation about the solution remained, but this was ignored). The initial conditions were that the flow velocity was zero everywhere and the surface elevation was also zero everywhere except at the boundary of the model across the south of the Gulf, which was assumed to have an initial slope similar to that

¹ Bye, J. A. T., 1975. Thalasso-scale numerical modelling. Computer Report. School of Earth Sciences. The Flinders University of South Australia. (Unpublished.)

² Bullock, D. A. 1973. The general circulation of St. Vincent and Spencer Gulf. Honours Thesis, The Flinders University of South Australia. (Unpublished.)

developed later in the adjacent part of the Gulf. The boundary slope was found to have little effect on the current distribution and so the assumption is presumed to not have serious consequences.

The resultant depth-average current, which is the transport divided by the depth, was obtained at each point of a grid system formed over the Gulf, in polar form so that the magnitude and direction of the current could be seen immediately. The grid length was 6.4 km.

$$u(z) = \frac{U}{H} + \frac{g^*}{f} \frac{\partial \sigma_t}{\partial y} \left(z + \frac{H}{2} \right) \quad (4)$$

$$v(z) = \frac{V}{H} - \frac{g^*}{f} \frac{\partial \sigma_t}{\partial x} \left(z + \frac{H}{2} \right) \quad (5)$$

Applying equations (4) and (5) at $z = \eta \approx 0$ and at $z = -H$ gives the surface and bottom currents.

Since σ_t is independent of z it can be seen from equations (4) and (5) that the vertical homogeneity of the Gulf implies that the current is a linear function of depth z . Thus a shear current exists. The right-hand side of equation (4) and (5) can be interpreted as follows. The second terms are symmetric about a line marking mid-depth (Fig. 4) and give, as a function of depth, the current which is directly related to the local distribution of density. The first terms on the right-hand side of the equations, on the other hand, represent the depth-average current predicted by the model under the constraints imposed by the boundaries of the Gulf (the shores and bed).

The vertical components of velocity were also found, using the bottom current and the gradients of the bottom topography,

$$w = u_B \frac{\partial H}{\partial x} + v_B \frac{\partial H}{\partial y} \quad (6)$$

Finally, the changes in the sea level which develop from the initial surface condition of zero slope are also obtained.

Results of the Numerical Model

(1) Predicted Velocity Fields due to Thermohaline forcing only

Fig. 5 shows the main features of the predicted depth-average current. The figure is consistent with the water mass analysis of the previous section, i.e. the circulation in the wide, southern part of Spencer Gulf consists of a clockwise gyre, water entering via the western side and leaving on the eastern side and the circulation in the northern end appears closed.

To gain a detailed picture of the velocity field in the Gulf, a routine was added to the program which printed out the surface and bottom currents. By involving the shallow water assumption, i.e. that the Ekman layer (the surface layer influenced by wind) and the layer of bottom frictional influence overlap (an assumption which is consistent with the waters' vertical homogeneity), it can be shown (Bullock 1973—footnote 2) that the current components at any level are given by,

The magnitude of the velocity vectors shown is typically about 0.07 ms^{-1} (ranging from zero to 0.15 ms^{-1}).

From Figs 6 and 7, which show the surface and bottom currents respectively, it can be seen that at both the surface and bottom there is a very distinctive flow up the western side of the Gulf, which we shall call the "Port Lincoln Boundary Current". This current is broader in extent at the surface than at the bottom where it tends to peel away to the east down the slope of the bottom. The Port Lincoln Boundary Current is also somewhat stronger at the surface than at the bottom due to the frictional influence of the latter.

The direction of the bottom current can be seen to swing eastward and then to the south-east over a broad area before flowing southward to exit down the shovel-shaped topography through the Gulf's mouth. The surface current displays a similar pattern; however, since the Port Lincoln Boundary Current is wider at the surface, particularly near the mouth, the centre of the gyre of the surface circulation is located further to the north-east than the centre of the bottom gyre. Evidence of the eastward movement of water from the boundary current is also provided by Fig. 3a-c where the contours bulge to the east in this area.

The differences between the top and bottom current gyres implies that the surface and bottom currents on the eastern side of the Gulf are, in general, at an angle to each other, unlike the western boundary. This explains why there is no obvious salinity or σ_t tongue indicating a return flow down the eastern side of the Gulf in Fig. 3b and c.

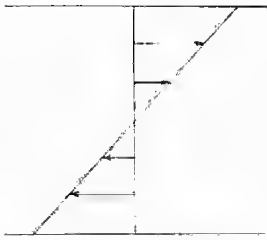


Fig. 4. Current as a function of depth, with reference to mid-depth.

Another important feature to be noted from Figs 6 and 7 is that in the centre of the mouth the surface and bottom currents are in opposite directions so that a large shear is predicted here. The closeness of the density and salinity sections (Fig. 2b and 2a) to those of a two-layer system is also explained by this phenomenon. It would be interesting to make direct current measurements in this area.

Further north, where the Gulf starts to narrow (at about the latitude of Wallaroo), the flow pattern is more complicated and conver-

gences of the currents exist. A large proportion of the water in the northern end appears to recirculate in a vertical gyre. Fig. 8, which shows the vertical components of velocity, lends support to this interpretation by the downwelling at the top of the Gulf near Point Lowly, which corresponds to an inflexion in the salinity contours (Fig. 3a). In the southern part of the Gulf, a complex system of vertical cells of typical dimension 20 km is predicted.

The following changes in surface elevation are predicted by the model: in the southern part of the Gulf, a low develops, the sea level on the western side being between 10 and 50 mm higher than in the centre; the sea level also increases to the north. We can conclude that the circulation in Spencer Gulf which can be attributed solely to thermohaline causes is of significant magnitude and forms a major contribution to the water exchange processes of the Gulf.

(2) *Velocity field due to Thermohaline and Wind Forcing*

The numerical experiment was now extended to include the effect of wind stress in addition

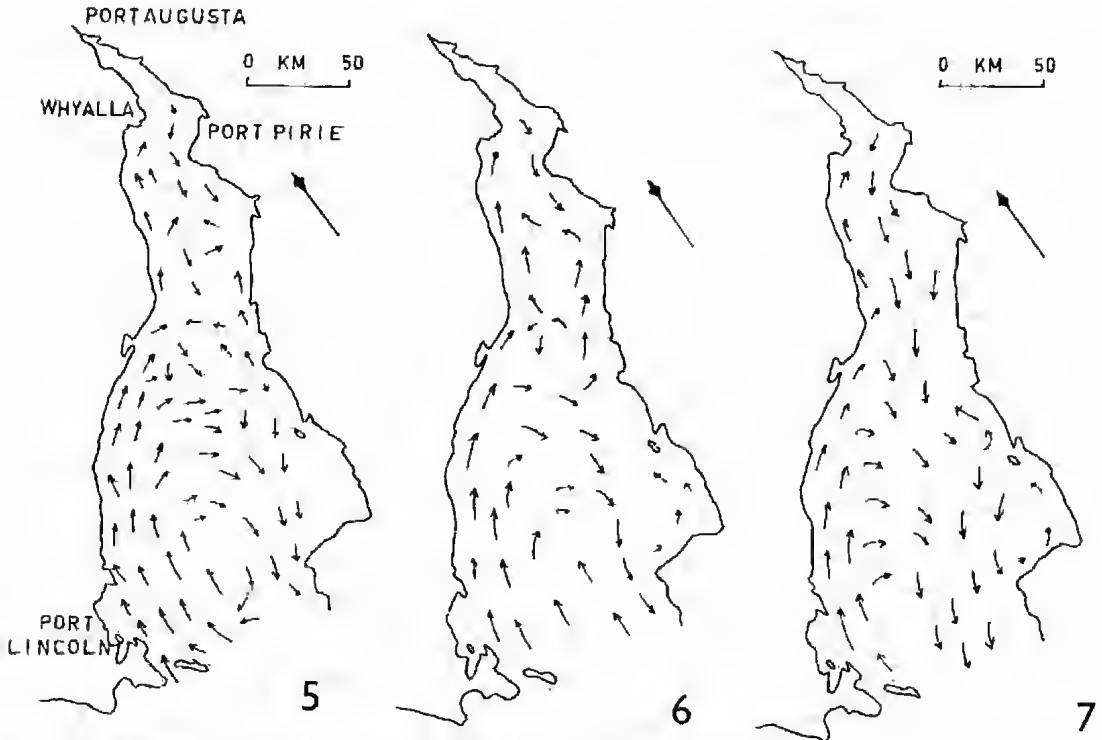


Fig. 5. Predicted depth-average thermohaline currents in Spencer Gulf.

Fig. 6. Predicted surface thermohaline currents in Spencer Gulf.

Fig. 7. Predicted bottom thermohaline currents in Spencer Gulf.

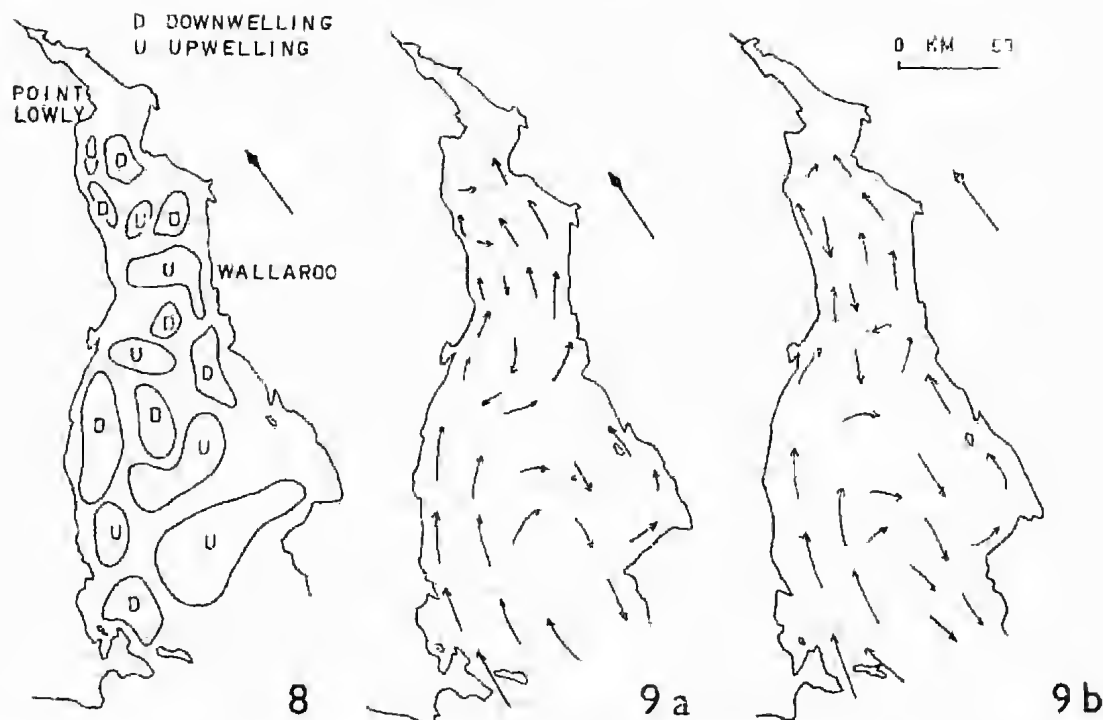


Fig. 8. Predicted regions of up- and down-welling due to thermohaline currents in Spencer Gulf.
 Fig. 9. Predicted currents in the presence of a 14 ms^{-1} SW wind.
 (a) Surface, (b) Bottom.

to the thermohaline forcing. The resulting surface and bottom currents predicted by the model for the same density structure as before, combined with a 14 ms^{-1} south-west wind, are shown in Fig. 9a and 9b.

The pattern of circulation is basically the same but the velocity of the flow is accentuated, being typically about 0.16 ms^{-1} , some velocity vectors having a magnitude over 0.30 ms^{-1} . Differences to the no-wind case do occur in the northern part of the Gulf where the surface current is predominantly northward in direction, particularly on the eastern side where it was directed southwards previously. Similarly the bottom current flows north adjacent to the shores, whereas in the no-wind case the bottom current was slight here. It can also be seen that with the wind added, the surface and bottom currents are almost the same everywhere.

The model predicts that the surface elevation increases greatly (up to 0.37 m) with distance up the Gulf, i.e. the water is piled up at the northern end by the wind. The low in the southern half is also accentuated, the level being raised by up to 80 mm around the shores

compared with the depression of 10 mm in the centre.

(3) Possible reasons for the Persistence of the Density Structure

In the numerical model, the thermohaline forcing terms remained constant throughout the period from zero velocity to equilibrium; i.e. we assume that the observed density field persists and is not an instantaneous feature which subsequently runs down until the Gulf becomes a completely homogeneous body of water in which water motion of thermohaline origin would cease.

It is surmised that the cause of the persistence of the thermohaline circulation is external, i.e. it is due to water from the Southern Ocean moving up under influences that determine the pattern of flow in this region, perhaps the prevailing westerly winds. Fig. 12, which shows the dynamic topography of the ocean south of Australia (Bye 1971), indicates that the direction of the geostrophic flow in the deep ocean is, in fact, basically perpendicular to the Australian coastline.

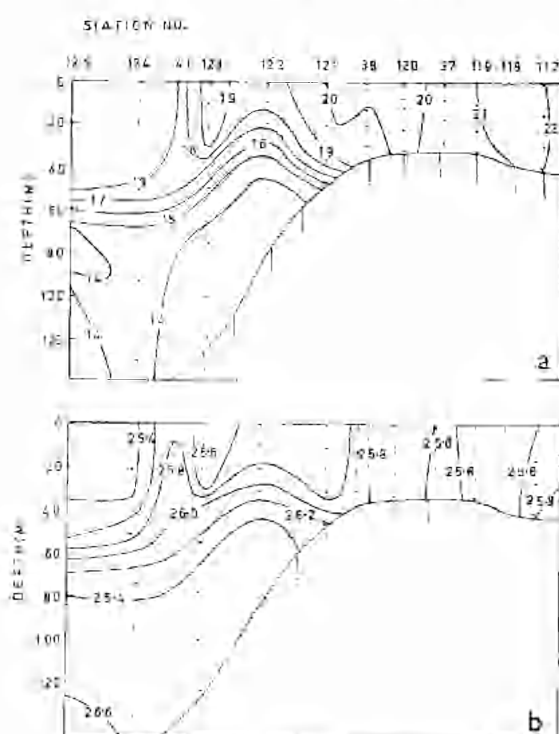


Fig. 10. Vertical sections along Investigator Strait to the Continental Slope. Marked --- on Figure 1, data taken from CSIRO Aust. 1966 and 1967a. Sampling depths indicated by dots.
(a) Temperature ($^{\circ}\text{C}$), (b) σ_t .

The other factor which exerts a continuous effect on Spencer Gulf is evaporation, which has the effect of maintaining a high salinity and hence a high density at the northern end. It is worth noting that in Fig. 3a the salinity tongue extending downward from the Gulf's northern end occurs over a favourable bottom gradient, whereas this is not so for the tongue which corresponds to the Port Lincoln Boundary Current.

(4) The Region Outside Spencer Gulf

The locations of measurements made in the area outside Spencer Gulf are shown in Fig. 1. Data from this region were obtained primarily to aid the fishing industry and suffer from the drawback that there are no synoptic surveys of the whole area, which would enable horizontal distributions of properties to be drawn. Only vertical sections and profiles can be satisfactorily constructed. The paths along which sections have been drawn are shown by the various lines in Fig. 1.

Fig. 10a and b show temperature and σ_t sections drawn along a line extending through Investigator Strait to past the end of the Continental Slope. The data were obtained in Feb.-March 1961 (C.S.I.R.O. Aust. 1966) and March 1963 (C.S.I.R.O. Aust. 1967a). One feature which is noticeable is the change in pattern from a vertically homogeneous situation just inside the mouth of Investigator Strait to the more complicated horizontal stratification in the deeper waters outside the Gulf.

The most significant feature shown by these sections, however, is the gradient in salinity, temperature and density about Station 122, which was located north-east of Cape Borda on the north-west tip of Kangaroo Island. This density gradient implies the existence of a thermohaline current, water to the west of Station 122 flowing approximately perpendicular to the plane of the section (into the page). This direction correlates very closely with the direction of the thermohaline current entering Spencer Gulf which forms the Port Lincoln Boundary Current. Conversely there is also a southward directed flow between Stations 121 and 122 which could have its origins in the outflow from the eastern side of Spencer Gulf. It is possible that upwelling is also occurring near the longitude of Station 122. The peak in the density lines for the surface water under Station 41 is explained by the fact that this station was occupied in a different year to the adjacent stations (although at the same time of the year), so that the surface water temperatures are not consistent.

The section shown in Fig. 11a and b runs roughly in a north-east direction from the Continental Shelf up Spencer Gulf (C.S.I.R.O. Aust. 1967a). The gradient of the lines adjacent to the rapidly deepening region outside Spencer Gulf under Station 64 again indicates a current inwards across the plane of the section, probably angled up slope so that the water inundates the more level sea bottom of Spencer Gulf. This is again in agreement with the previously deduced direction of flow into Spencer Gulf which is NNW and thus crosses the line of the section.

Fig. 12 shows that the direction of the circulation in the Southern Ocean is consistent with the flow in the region outside the Gulf as deduced from Figs 10 and 11.

Conclusion

The various data presented were mainly collected in the months of February to May,

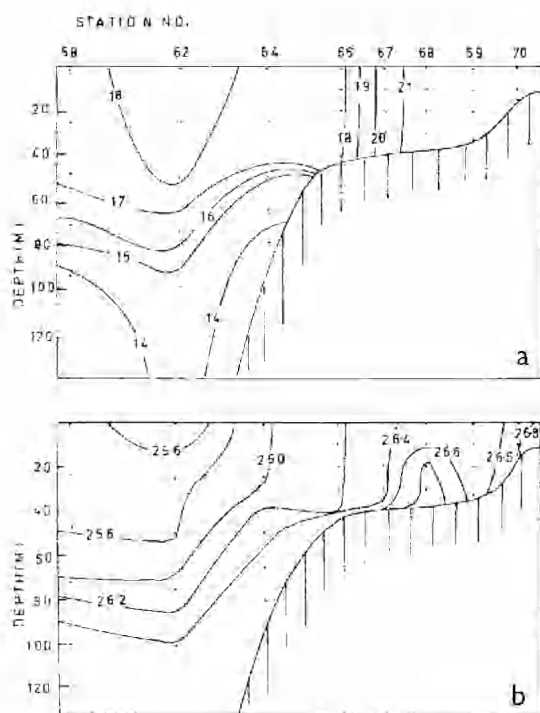


Fig. 11. Vertical sections along Spencer Gulf to the Continental Shelf. Marked — on Figure 1, data taken from CSIRO Aust. 1967a. Sampling depths indicated by dots.

(a) Temperature ($^{\circ}\text{C}$), (b) σ_t .

although during different years, so that it would appear that the general circulation deduced occurs at least seasonally. However, to gain a complete and detailed picture of the circulation in the Gulf, it is obviously necessary to conduct a series of thorough cruises at various times throughout the year. In addition, direct current measurements need to be made to check the results from the model. Since the dis-

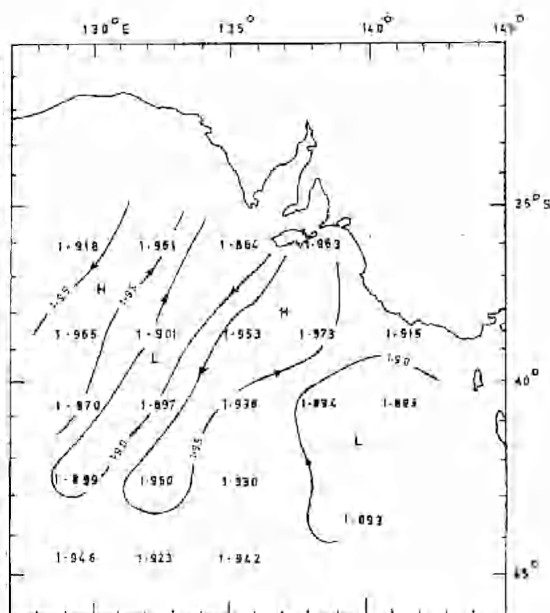


Fig. 12. Dynamic topography relative to 2000 db., south of Australia (taken from Bye 1971).

tributions of water properties in St Vincent Gulf have been found (Bullock 1974) to be similar to those in Spencer Gulf, it may be expected that the general circulation in St Vincent Gulf would also display a pattern basically similar to that in Spencer Gulf.

Acknowledgement

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